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March 1998

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Ecosystem Management and Restoration Research Program

Evaluation of Flow-Resistance Equations for Vegetated Channels and Floodplains

by Syndi J. Flippin-Dudley, Steven R. Abt, Charles D. Bonham, Chester C. Watson, Colorado State University

J. Craig Fischenich, WES

Prepared for Headquarters, U.S. Army Corps of Engineers

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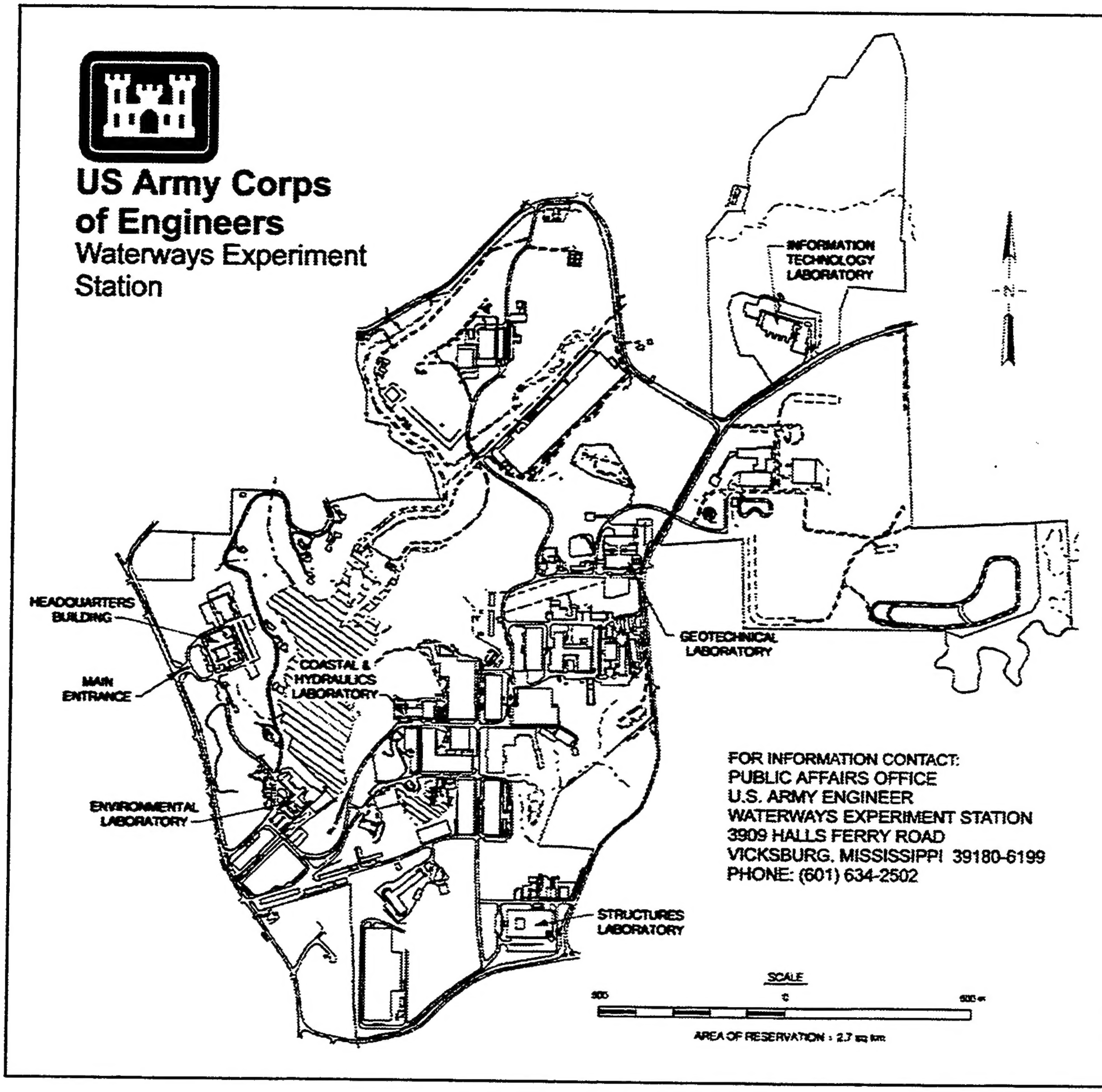

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Ecosystem Management and Restoration

US Army Corps
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Vegetation Resistance

Evaluation of Flow-Resistance Equations for Vegetated Channels and Floodplains (TR EL-98-2)

ISSUE: Several methods have been proposed for determining Manning's n in vegetated channels. These methods recognize that the physical characteristics of the vegetation are important factors in evaluating flow resistance. However, minimal research has been conducted to quantify the density and drag characteristics of vegetation.

RESEARCH OBJECTIVES: The objectives of the research presented in this report were to develop and evaluate methods of computing flow resistance in vegetated channels and floodplains and to characterize the impacts of vegetation for flows in a channel typical of most temperate floodplains.

SUMMARY: A field study was performed in a vegetated channel located near Stillwater, OK, as a part of the development of a comprehensive approach to predicting resistance to flow using the Fischenich equation. The channel was characterized for geometry, slope, and vegetation density. A series of nine flows was conveyed through the channel, and velocity and depth measurements were obtained for two vegetative conditions: (a) without leaves on trees and shrubs and with vegetative debris present, and (b) with leaves on trees and shrubs and without vegetative debris.

The vegetation and flow measurements were used to develop a relation between the coefficient of drag and Reynolds number, Re, for the two conditions investigated. For Re 2×10^6, the drag coefficient associated with the latter condition was approximately equal to one, which is consistent with laboratory model test results reported by others. The drag coefficient for a specified Re was 10.2 times greater for the former condition primarily due to the presence of debris. The relations for drag can be input into the Fischenich equation to solve for Manning's n for channels with similar vegetative conditions. Manning's n was predicted within an average of 10 percent for four streams located in Mississippi and Alabama using the approach.

AVAILABILITY OF REPORT: The report is available on Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199; telephone (601) 634-2355.

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About the Authors: Drs. Syndi J. Flippin-Dudley, Steven R. Abt, Charles D. Bonham, and Chester C. Watson are with the Department of Civil Engineering at Colorado State University. Dr. J. Craig Fischenich is a research civil engineer at the WES Environmental Laboratory. Point of contact is Dr. Fischenich at (601) 634-3449.

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Preface

The work described in this report was authorized by the Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Ecosystem Management and Restoration Research Program (EMRRP), Work Unit 32880. Program Monitors were Ms. Beverley Getzen, Mr. Pete Juhle, Ms. Cheryl Smith, and Ms. Denise White, HQUSACE.

Mr. Dave Mathis (CERD-C) was the EMRRP Coordinator at the Directorate of Research and Development, HQUSACE. Dr. Russell F. Theriot, Environmental Laboratory (EL), U.S. Army Engineer Waterways Experiment Station (WES), was the EMRRP Manager, and Mr. Robert L. Lazor was Assistant Manager.

This report was prepared by Drs. Syndi J. Flippin-Dudley, Steven R. Abt, Charles D. Bonham, and Chester C. Watson, Department of Civil Engineering, Colorado State University, and Dr. J. Craig Fischenich, Environmental Resources Engineering Branch (EREB), EL. Technical review was provided by Ms. Trudy L. Olin and Mr. E. A. Dardeau, Jr., EL.

The study was performed under the supervision of Mr. Thomas R. Patin, Chief, EREB; Mr. Norman R. Francingues, Chief, Environmental Engineering Division, EL; and Dr. John Harrison, Director, EL.

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List of Symbols

a	coefficient that is absorbed by the drag coefficient
a_i	cross-sectional area of ith partial section
A	cross-sectional area of flow
A_B	cross-sectional area of belt transect
A_i	frontal area of the ith vegetal element
C_d	drag coefficient
$\bar{d}_i$	mean diameter of individual plant element
D	distance in which a point is advanced through vegetation
Deb_d	debris density
g	gravitational acceleration
h_v	velocity head
j	number of cross sections
k_n	a coefficient equal to 1.486 for English and 1 for SI units
L	characteristic channel length
n	Manning's roughness coefficient
Q	discharge
Q_i	discharge for ith partial section
R	hydraulic radius
R^2	coefficient of determination for regression function
Re	Reynolds number
S_e	slope of the energy grade line
v_i	flow velocity for ith partial section
V	flow velocity
Veg_d	vegetation density
wse	water surface elevation
y	flow depth
y_i	depth of flow at individual plant element

α energy coefficient

ν kinematic viscosity

z section factor

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831	cubic meters
feet	0.3048	meters
inches	25.4	millimeters
miles (U.S. statute)	1.609347	kilometers
pounds (force per square foot)	47.88026	pascals
pounds (mass)	0.4535924	kilograms
square feet	0.092903	square meters

1 Introduction

During the past decade, the conventional "flood control" ideology has evolved into a philosophy of "flood management." Streams are valuable economic assets to communities. An effective flood management program must consider environmental, recreational, and aesthetic issues in addition to flood control. Riparian vegetation is an integral component of the flood channel. Vegetation stabilizes streambanks, provides shade that prevents excessive water temperature fluctuations, supports wildlife, and performs an essential role in nutrient cycling and water quality.

Concurrent with the benefits provided by riparian vegetation are the issues pertaining to flood hazard mitigation. Vegetation increases flow resistance, which has an inverse effect on the discharge capacity and the level of flood protection provided by the channel. Several methods have been proposed for determining Manning's n in vegetated channels. These methods recognize that the physical characteristics and growth patterns of the vegetation are important factors in evaluating flow resistance. However, little guidance is available to quantify the physical properties of the vegetation that affect flow resistance. A cooperative study between the U.S. Army Corps of Engineers and Colorado State University was conducted to develop a method of characterizing vegetation for the purpose of determining resistance to flow in open channels or floodplains.

Background

In the United States flow resistance is customarily expressed in terms of the resistance coefficient Manning's n. The resistance coefficient is used in Manning's Monomial Equation for mean flow velocity V (Manning 1891)

$$V = \frac{k_n}{n} R^{2/3} \sqrt{S_e} \tag{1}$$

where

k_n = coefficient equal to 1.486 for English and 1 for SI units
R = hydraulic radius
S_e = slope of energy grade line

The primary difficulty in using Equation 1 is accurately estimating the value of the resistance coefficient. Only limited guidance is available for selecting resistance coefficients, particularly in vegetated floodways.

Fischenich (1996) presented a comprehensive review of the methods available for selecting a roughness coefficient for vegetated floodways and concluded that the existing methods do not permit an accurate assessment of flow depth and velocity. Based on conservation of momentum principles, he suggested that an appropriate relation to evaluate flow resistance in channels with nonsubmersed vegetation is

$$n = k_n R^{2/3} \left[\frac{C_d Veg_d}{2g} \right]^{1/2} \tag{2}$$

where

C_d = coefficient to account for drag characteristics of vegetation
Veg_d = vegetation density
g = gravitational constant

Vegetation density is defined as

$$Veg_d = \frac{\sum A_i}{AL} \tag{3}$$

where

A_i = area of vegetation below water surface projected onto a plane perpendicular to direction of flow
A = cross-sectional area of flow
L = characteristic length, such as a unit length of channel

Equation 2 requires knowledge of the vegetation density and drag coefficient for the vegetation; however, little is known about the drag characteristics of vegetation. The vegetation density Veg_d can be directly measured using a horizontal point frame (Flippin-Dudley 1997). Figure 1 is a schematic drawing of the horizontal point frame. The frame consists of two vertical poles and three sets (two each) of cross arms, 1 m long and inclined at an angle of 45 deg. Each cross arm is fabricated with equally spaced holes that are aligned with the holes in the opposite cross arm through which a pin is guided. The pin is 0.3 m long and sharpened to a point at one end. Stakes attached to the lower ends of the poles allow the frame to be freestanding when staked into the ground.

The point frame is first staked at a random location within the area under investigation (a frame). The pin is slowly guided through each hole (a point) in the cross arms while all contacts made by the point of the pin with vegetation are recorded. The vegetation density Veg_d is

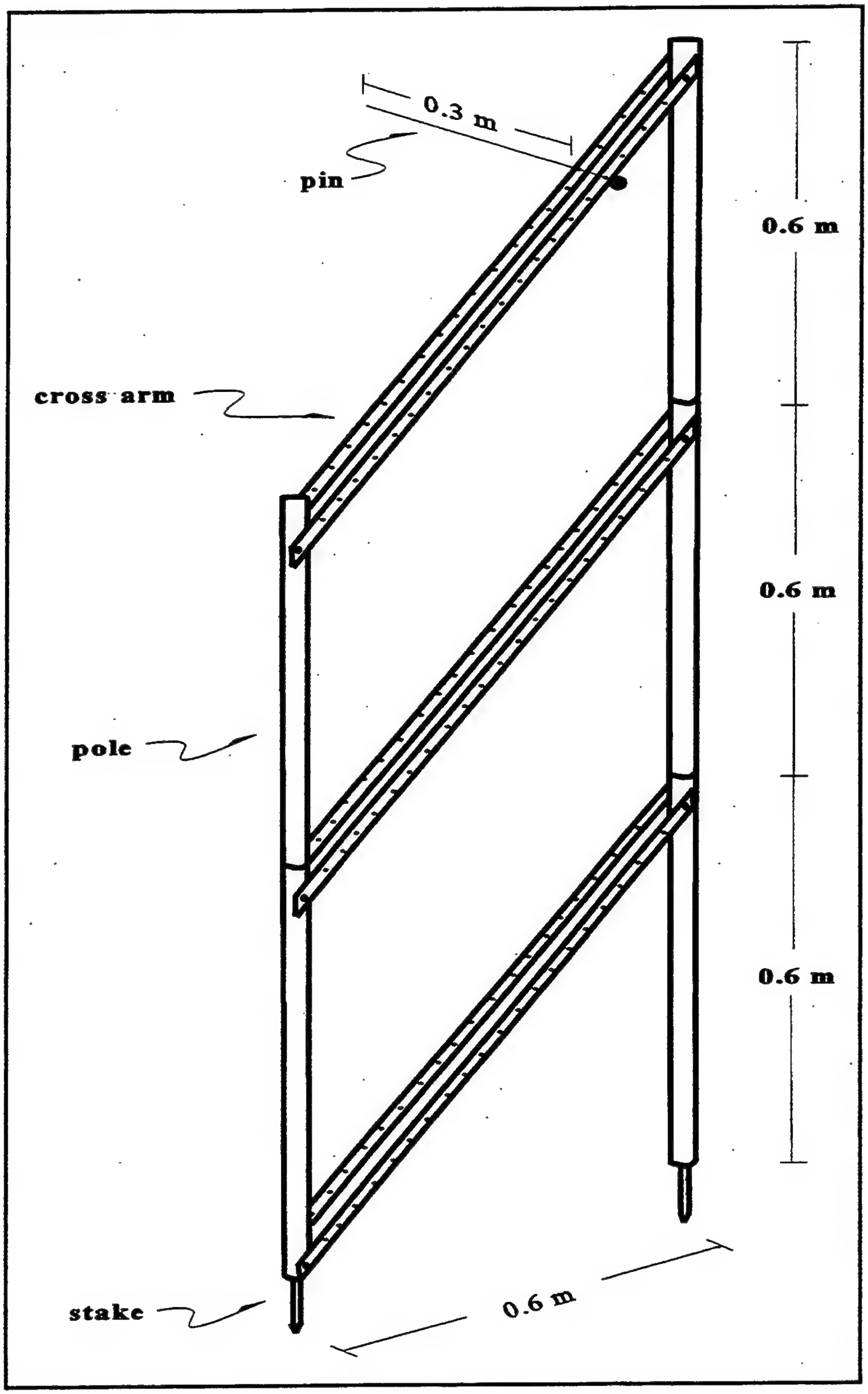


Figure 1. Horizontal point frame with three 0.6-m detachable sections

$$Veg_d = \frac{Number\ of\ Hits}{Number\ of\ Points}\left(\frac{1}{D}\right) \tag{4}$$

where D is the pin length. The procedure is repeated at least 10 times, or until the error of estimation of the vegetation density for the delineated area as determined by the running mean is less than 10 percent. Equation 4 applies independently of the number of frames or points per frame conducted. For example, if 200 hits are recorded by a total of 1,200 points using a 0.3-m pin, the Veg_d is 0.55/m (200 hits/1,200 points/0.3 m).

Study Objective

The objective of the study was to develop a comprehensive approach using Equation 2 to determine the Manning roughness coefficient for channels with nonsubmersed vegetation. In this study, the coefficient of drag was calculated from measured values of Manning's n, vegetation density, and hydraulic radius. Vegetation and flow measurements were conducted in a channel located at the Agricultural Research Service (ARS) Outdoor Hydraulic Laboratory in Stillwater, OK. The measurements were used to develop a relation for the drag characteristics of the vegetation C_d that can be directly input into Equation 2 for determining Manning's n. The approach was then substantiated using data for four streams located in Mississippi and Alabama.

2 Field Test and Application

The horizontal point frame was applied to measure the density of vegetation in a channel located at the ARS Outdoor Hydraulic Laboratory near Stillwater, OK. Vegetation and flow measurements were used in conjunction with Equation 2 for estimating resistance to flow (Manning's n) for channels in which the vegetation is not submersed. In Equation 2, Manning's n is expressed as a function of the flow depth, channel/floodplain geometry, vegetation density, and drag coefficient. In practice, the flow depth and channel geometry are usually known. The horizontal point frame can be used to measure the vegetation density Veg_d. Little is known about the drag characteristics of vegetation, although extensive information is available concerning the coefficient of drag for common objects and shapes (e.g., Blevins 1984).

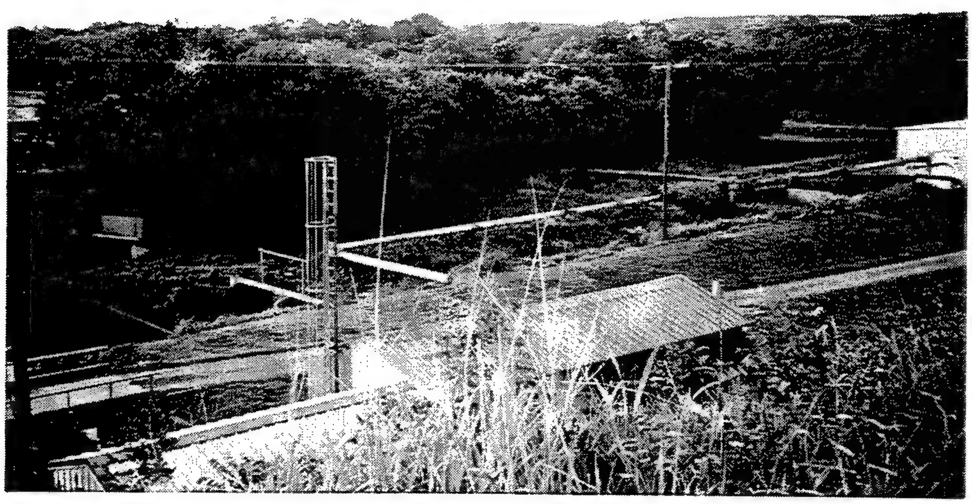
In this study, the horizontal point frame was used in conjunction with flow measurements in a vegetated channel to develop a relationship for the drag coefficient of vegetation that can be used in Equation 2 for determining Manning's n. Four trips were taken in conjunction with the testing—two in August 1995, one each in November 1995 and June 1996. The purpose of the first trip in August 1995 was reconnaissance to establish locations of six flow measurement cross sections. During the August 1995 trip, cross sections and channel slope were surveyed, plant samples were collected, and preliminary vegetation measurements were obtained. Detailed vegetation measurements were conducted in June. Flow measurements were conducted in both November 1995 and June 1996.

Test Channel

History

The field tests were conducted at the ARS Outdoor Hydraulic Laboratory located approximately 10 km west of Stillwater, OK. Figure 2 shows the test channel in November 1995 and June 1996. The test channel was constructed between 1942 and 1944 on a hillside composed of heavy clay soil at the base of the Carl Blackwell Dam. Water is conveyed from the lake through five siphons, each having a maximum capacity ranging between 0.57 and 0.85 m^3/s, depending on the water level of the reservoir. The siphon flow rate is measured using an ogee crest weir structure at the outlet. Downstream from the weir, the water

a. November 1995



b. June 1996

Figure 2. Test channel in Stillwater, OK

flows by gravity through a main distribution channel and enters the test channel through a 3-m sluice gate. At the terminus of the test channel, the water is released into another channel that discharges into Stillwater Creek.

The original channel was 117 m long and divided into three reaches by slope. The upper reach was originally graded at a 3-percent slope for 41 m. The 47-m-long middle reach was constructed at a 6-percent grade and the 30-m-long lower reach was graded at a 4-percent slope. The cross section was V-shaped, 0.6 m deep, and 12 m wide with 1:10 side slopes (Gwinn and Ree 1980).

During the period from 1944 through 1950, the channel was maintained by mowing and seeding with various types of grasses in association with a research program designed to determine the stability and capacity of a grass-lined channel. The results of this research were the ARS *n-VR* method for determining Manning's *n* for grass-lined channels (U.S. Department of Agriculture (USDA) 1954). The channel has not been maintained since 1950, and volunteer vegetation (i.e., trees, shrubs, and grasses, etc.) has been permitted to grow without interference.

Plant composition

Since 1951, the channel has become overgrown with vegetation typical of dense woods and thickets found in northwestern Oklahoma. Nineteen plant specimens were collected during August 1995. They consisted of eight tree, six grass and forb, one shrub, and two woody vine species (Tables 1 and 2).

The tree species, percent composition, and average diameter of each tree species are presented in Table 1. The average diameter of all trees measured was 10 cm. Only trees having diameters greater than 2.5 cm were measured. Dogwood (*Cornus drummondii*), elm (*Ulmus nubra*), and hackberry (*Celtis*

Table 1
Composition and Average Diameter of Trees in Stillwater, OK, Test Channel

Common Name	Scientific Name	Composition, %	Average Diameter, m
Dogwood	*Cornus drummondii*	33	0.05
Elm[1]	*Ulmus nubra*	21	0.19
Hackberry	*Celtis tenuifolia*		
Red Cedar	*Juniperus virginiana*	15	0.07
Honey Locust	*Gleditsia triacanthos*	11	0.17
Unknown (dead)	Unknown	8	0.04
Pecan	*Carya pecan*	5	0.11
Upland Sumac[2]	*Rhus copallina*	5	0.04
Smooth Upland Sumac	*Rhus glabra*		
Willow	*Salix* spp.	2	0.19

[1] No distinction made between elm and hackberry.
[2] No distinction made between upland and smooth upland sumac.

Table 2
Composition of Grasses and Forbs, Shrubs, and Woody Vines in Stillwater, OK, Test Channel

Plant Group	Common Name	Scientific Name	Composition, %
Grasses and Forbs	Verrain Prairie Sage Poverty Oak Grass Sedge Canada Goldenrod Rice Cut-Grass	*Verbena scabra* *Artemisia eudoviciana* *Danthonia spicata* *Carex* spp. *Solidago canadersis* *Leersia virginica*	50
Shrubs	Huckleberry	*Vaccinium pallidum*	36
Woody Vines	Carolina Moonseed Poison Ivy	*Cocculus carolinus* *Toxicodendron rydbergii*	14

tenuifolia) comprised more than 50 percent of the trees in the test channel. These species were present throughout the entire length of the channel. Red cedar (*Juniperus virginiana*), comprising 15 percent of the trees, was most prevalent in the lower reach of the channel. The red cedar exposed to the sun on the channel margins appeared healthy. Cedar trees inside the canopy were devoid of leaves and often dead, apparently due to a lack of sunlight or flooding. Sumac (*Rhus glabra and Rhus copallina*) and honey locust (*Gleditsia triacanthos*) comprised 5 and 11 percent of the trees, respectively, and were common in the upper and middle reaches of the channel. Pecan (*Carya illinoensis*) and willow (*Salix* spp.) comprised 5 and 2 percent of the trees in the channel, respectively, and were only encountered in the lower reach of the channel.

The term composition has a different meaning in Table 1 than in Table 2 because the tree group was evaluated separately from the other three plant groups. In Table 2, the composition is the percentage of the stand comprised by each plant group. That is, 50 percent of the vegetation encountered (excluding trees) was grasses and forbs, 36 percent was shrub, and 14 percent was woody vine. Grasses and forbs were found throughout the channel, particularly in areas exposed to sunlight such as the channel's edge, but were concentrated in the area of the grade break between the upper and middle reaches and near the channel's end. None of the original grasses planted in the channel as a part of the research conducted in the 1940s were observed. The only shrub encountered was the huckleberry (*Vaccinium pallidum*), which was prevalent throughout the channel. The two woody vines, poison ivy (*Toxicodendron rydbergii*) and Carolina moonseed (*Cocculus carolinus*), were abundant in the lower reach.

Channel survey

Six cross sections were established and surveyed in August 1995 (Figure 3). The surveyed channel profile and a typical cross section of the test channel are shown on Figures 4 and 5, respectively. The channel profile and geometry are similar to the original shape. The 117-m-long channel can be divided into three reaches according to slope. Cross sections 1 through 4 are approximately 12 m

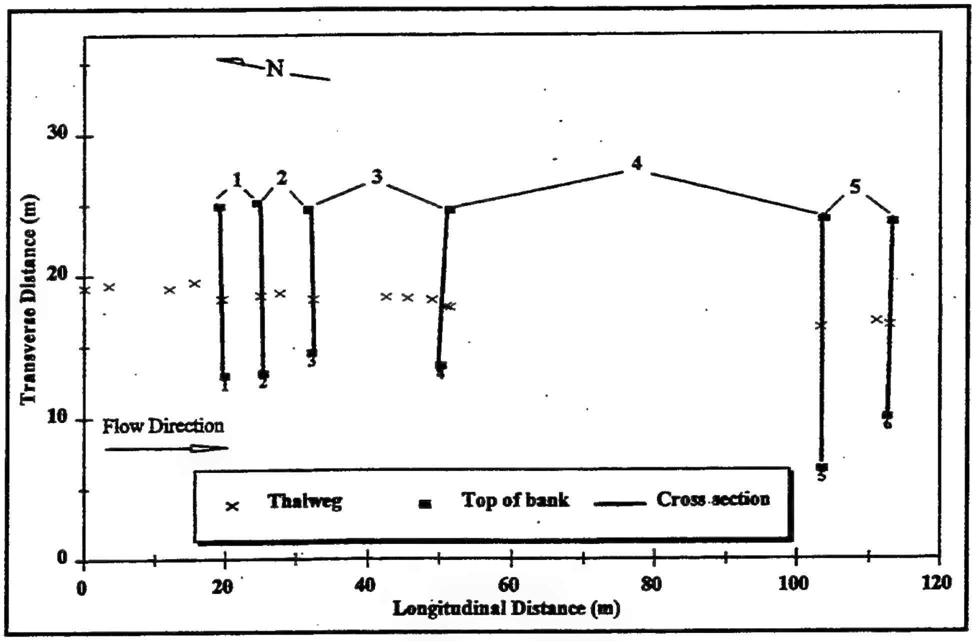


Figure 3. Plan view of channel showing five reaches and six cross sections

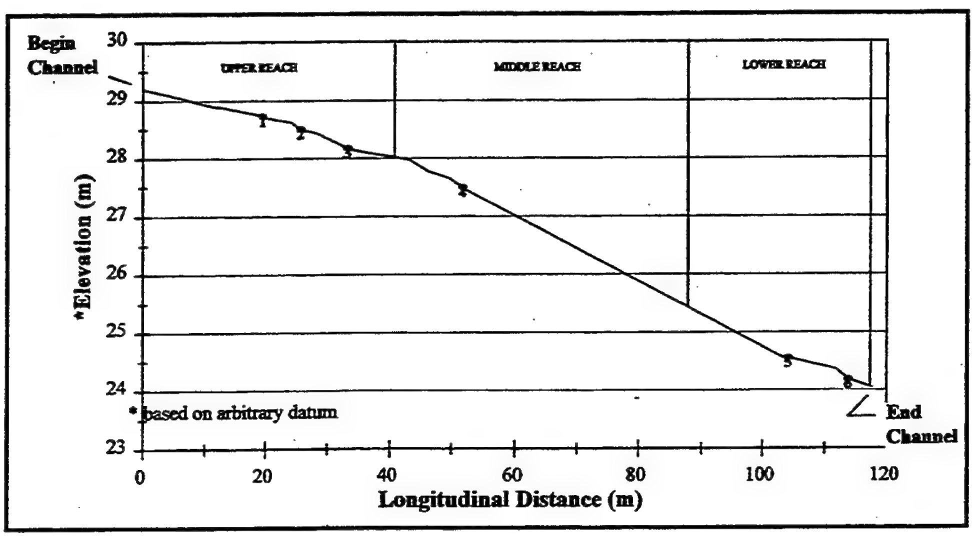


Figure 4. Profile of channel showing lower, middle, and upper reaches and six cross sections

wide, 0.6 m deep, with 1:10 side slopes. The channel gradually widens to approximately 18 m near sections 5 and 6.

A strip gully, approximately 0.3 to 0.6 m wide, forms a well-defined thalweg that roughly follows the center of the channel (Figure 3). The gully meanders around trees and large roots and was likely formed by runoff during rainstorms or leakage under the sluice gate from the main distribution channel.

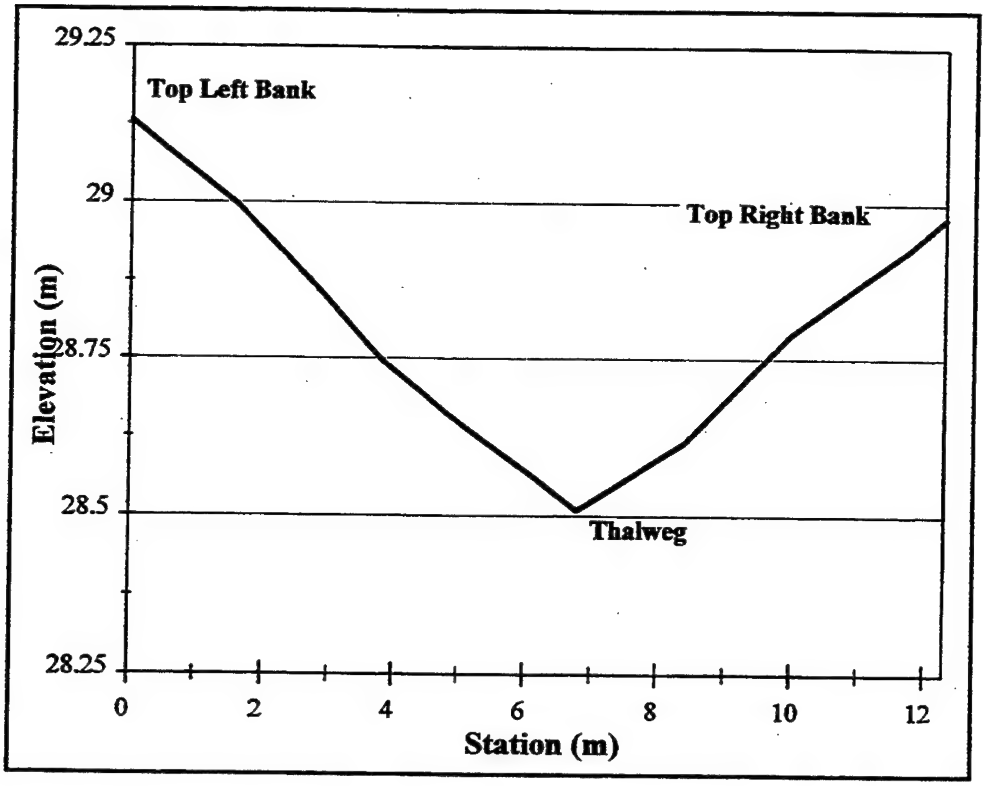


Figure 5. Typical cross section, Stillwater, OK, test channel

Vegetation Density Measurements

Vegetation density measurements were conducted in the test channel in August 1995 and June 1996. During the initial assessment, measurements were taken at each of the six cross sections, and tree diameters were recorded at random locations. These data were used to assess the general character of vegetation in the channel. A more intense examination of the vegetation was conducted during June 1996; these latter measurements served as the basis for the vegetation analysis presented.

Vegetation measurements were taken up to a height of 0.6 m above the thalweg because the maximum depth of flow in the test channel was not expected to exceed this height. Measurements were conducted using two techniques: (a) the horizontal point frame and (b) direct measurement of tree trunks. Grass and forb, shrub, and vine plant groups were measured using the horizontal point frame. Trees were measured by both the horizontal point frame method and direct measurement of diameter. All leaves, stems, and tree parts and trunks less than 2.5 cm in diameter were included in the point frame measurements. Tree trunks greater than 2.5 cm in diameter were measured directly in November 1995 (when leaves on the trees and shrubs were absent) to determine the Veg_d.

Horizontal point frame measurements

Horizontal point frame measurements were taken using the line transect method. The line transect method is a systematic sampling technique that consists of establishing a line across the channel and placing the point frame at specific intervals along the line. Thirteen line transects were established (Figure 6). The line transects were marked by a cloth surveying tape extended across the channel at a height of 0.6 m above the thalweg. The length of the transects varied from 9 to 14 m according to the channel cross-sectional characteristics at each transect (Table 3).

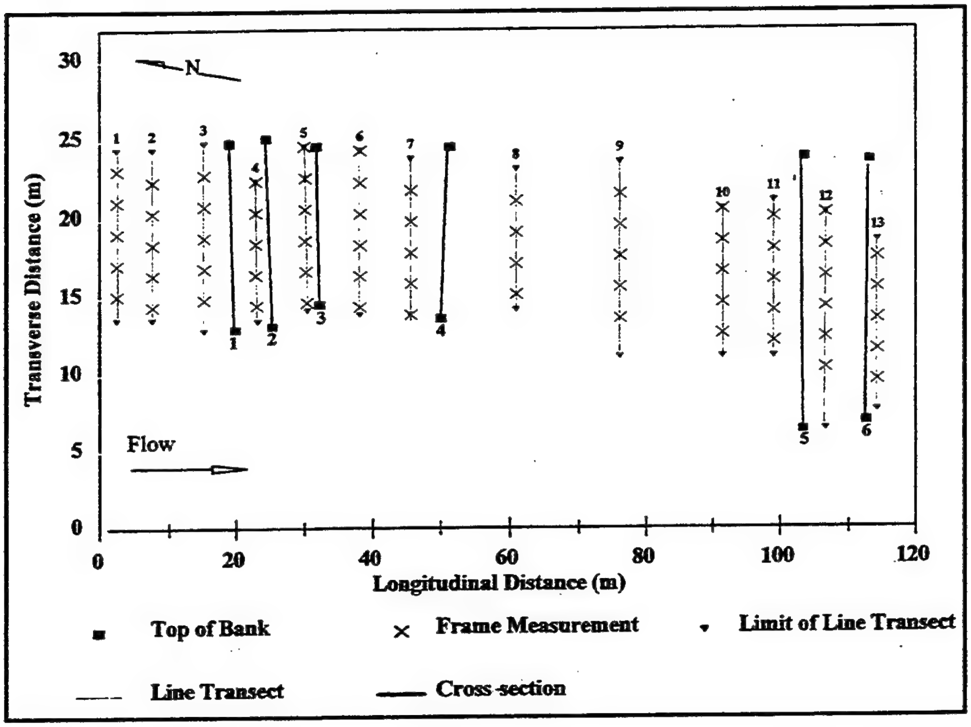


Figure 6. Plan view of channel depicting six cross sections and 13 line transects along which vegetation density measurements were obtained using horizontal point frame

Four to six point frame measurements 2 m apart were taken along each transect, and Table 3 summarizes the data for the 13-line transects. Measurements were taken with the lowest cross arm of the horizontal point frame (Figure 1) since the maximum depth of flow was expected to be 0.6 m. The frame was placed adjacent to the line, and points were inserted up to the height of the tape. The number of points used per frame depended on the height of the tape above the channel bottom at each location, and varied from a minimum of 4 points/frame near the edges of the channel to a maximum of 20 points/frame at the thalweg.

Out of a total of 906 points (67 frames), 158 hits were recorded. Sixty-eight hits were made with grass or forb, 19 with vines, 48 with shrub, and 23 with trees

Table 3
Summary of Horizontal Point Frame Measurements Conducted in Stillwater, OK, Test Channel

Line Transect No.	Longitudinal Station, m	Length of Line Transect m	Number of Frames	Number[1] of Points	Number of Hits						
					Grass or Forb	Vine	Shrub		Tree		
						Leaf	Stem	Leaf	Stem	Leaf
2	7.6	11	5	76				7		1
3	15	12	5	59				6		
4	23	9	5	71	6			2		
5	30	10.5	6	70	16			4		
6	38	10.5	6	76	1		2	3	3	
7	46	10	5	58	14				3	2
8	61	9	4	62			1	4		2
9	76	10	5	70	4		1	5		
10	91	9.5	5	45			1	1	1	
11	99	10	5	70	1	2			2	
12	107	14	6	91	7	3	2	3	3	4
13	114	11	5	70	16	9	2	4		2
Total			62	818	65	14	9	39	12	11

[1] Number of points per frame varied.

(excluding contacts with tree trunks greater than 2.5 cm in diameter). The density of the vegetation measured with the point frame as calculated from Equation 4 is 0.581/m (158 hits/906 points/0.3 m).

Tree measurements

Belt transects were established at line transects 2 through 13 for the purpose of determining the contribution of tree trunks greater than 2.5 cm in diameter. A belt transect is a rectangular-shaped or strip quadrat. The belt transects in this study were oriented with the long dimension perpendicular to the flow direction. The dimensions were 9 by 3 m (1.5 m upstream and downstream of the line). A belt transect was not established in conjunction with the first line transect due to its close proximity to the channel entrance gate. The combined width of the 12 belt transects (36 m) represented over 30 percent of the total channel length (117 m). The tree species, location with the belt transect, basal diameter, and diameter at 0.6-m height were recorded. A total of 126 trees having a trunk diameter greater than 2.5 cm were identified within the 12 transects. Figure 7 presents a plan view of the test channel showing the location of the 12 belt transects (labeled 2 through 13) and trees in which the diameters were directly measured.

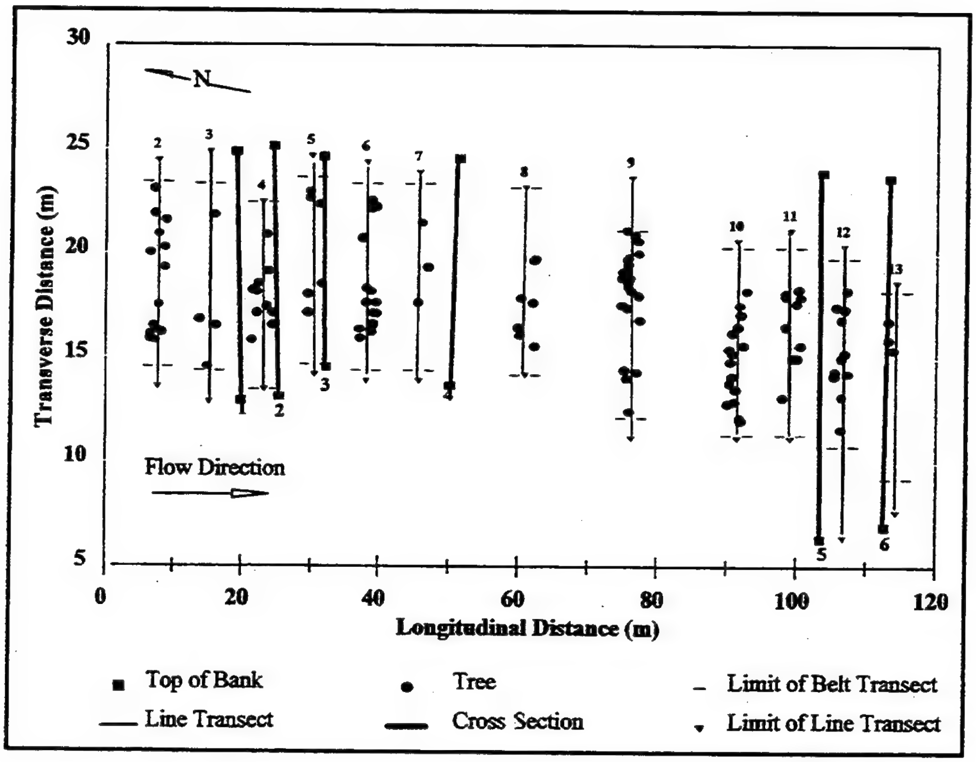


Figure 7. Plan view of test channel depicting six cross sections and 12 belt transects in which tree trunks >2.5 cm were directly measured

Table 4 contains a summary of the calculations to determine the contribution of the trees to the total Veg_d. The Veg_d of the tree trunks with greater than 2.5 cm in diameter was calculated as

Table 4
Summary of *Veg_d* Calculations for Tree Trunks Greater Than 2.5 cm in Diameter

Belt Transect No.	ΣA_i m^2	A_B m^2	Veg_d 1/m
2	0.611	4.279	0.048
3	0.634	3.337	0.063
4	0.930	3.770	0.082
5	0.395	3.682	0.036
6	0.258	4.020	0.021
7	0.055	3.214	0.006
8	0.544	3.590	0.051
10	0.652	2.665	0.082
11	0.855	3.907	0.073
12	0.232	4.553	0.017
13	0.055	3.958	0.005

$$Veg_d = \frac{\Sigma A_i}{A_B L} \quad (5)$$

where

A_i = projected area of an individual tree below water surface
A_B = area of flow represented by belt transect
L = length of belt transect, 3 m

The value of A_i was calculated by

$$A_i = y_i \bar{d}_i \quad (6)$$

where

y_i = depth of flow at individual tree
$\bar{d}_i$ = mean of tree basal diameter and diameter at 0.6 m

The flow depth at each tree y_i depends on the horizontal station of the tree within the transect because the channel cross section is generally triangular in shape. The value of y_i was determined from the vertical distance between the tape that marked the line transect (strung at a height of 0.6 m above the thalweg) and the base of the tree. The characteristic flow area A_B was calculated based on the channel geometry at the line transect and the width of the belt transect (9 m). Table 4 lists the total area of all trees, flow area, and vegetation density

associated with each belt transect. The mean Veg_d of the entire test channel due to tree trunks greater than 2.5 cm is 0.046/m. Summing the tree and horizontal point measurements yields a mean Veg_d for the entire channel of 0.627/m (0.046/m + 0.581/m).

The values of Veg_d for November were determined based on measurements conducted in June. The tree trunk measurements were used directly because the contribution of the tree trunks to the value of Veg_d does not change between seasons. The primary difference between the condition of the vegetation in November and June was that the tree and shrub leaves were not present. Therefore, all contacts with leaves, including grass, were excluded from the horizontal point frame measurements. Grass was present in the channel during the November test; however, it was not included in the Veg_d parameter because the density of the grass was not known. The effect of excluding the grass on the analysis of resistance are discussed in more detail in the section on assumptions of the methodology. The Veg_d used in the analysis for November was 0.123/m based on the tree trunk measurements and contacts made with stems using the point frame (0.077/m stems + 0.046/m tree trunks).

Assessment of vegetation density

Flippin-Dudley et al. (in preparation) recommended three steps for field application of the horizontal point frame: (a) delineation of area, (b) location of measurements, and (c) decision of sample size. The steps were applied to the vegetation measurements conducted in the test channel as follows:

a. *Delineation of Area* - The area in which the measurements are conducted should correspond to the length of channel in which the roughness characteristics are to be evaluated. In this study, the measurements were conducted throughout the entire length of the test channel. An average vegetation density was used because the vegetation (resistance) characteristics were similar throughout the channel.

b. *Location of Measurements* - Vegetation measurements were conducted based on systematic sampling methods using line transects for horizontal point frame data and belt transects for tree data. Measurements should be obtained by random sampling in the area under investigation to minimize the effects of trends in the vegetation; therefore, the data were randomized prior to analysis of sample size.

c. *Sample Size* - A plot of the running mean was used to assess the accuracy of the mean vegetation density. The method consists of plotting successive or "running" means against the number of measurements. Sampling should be continued until the percentage difference between the previous mean and the new mean is 5 percent or less. The minimum number of frames should correspond to that required to obtain either 100 hits with vegetation or 10 frames.

Plots of the running mean were prepared for the randomized horizontal point frame and tree data (Figure 8). The analysis of the data indicated that the difference in cumulative mean values was 2 percent after 30 frames. However, the number of hits with vegetation for 30 frames was 56, which is less than the specified minimum of 100. The number of frames required to obtain 100 hits with vegetation was 42. In this study, 67 frames were conducted, which is greater than the minimum of 42.

A mean vegetation density was plotted for the tree data based on the measurements conducted for each transect. The difference in cumulative mean values was 4 percent after eight belt transects. The number of belt transects required to obtain a count of 100 trees was 11. The actual number of belt transects analyzed was 12.

Flow Depth and Velocity Measurements

Flow depth and velocity measurements were conducted in November 1995 and June 1996. It was desired to determine the flow resistance characteristics of the channel in its existing condition in November and then again after the removal of vegetative debris and growth of green foliage in June. In both November and June, flow depth and velocity measurements were conducted for nine test discharges at each of the six cross sections. Each test discharge was preliminarily established based on static head measurements for a calibrated ogee crest weir located upstream of the channel entrance. The ninth discharge was less during June testing due to lower water levels in the water supply lake.

The flow depth and velocity measurements were conducted according to the procedures presented in the *National Handbook of Recommended Methods for Water-Data Acquisition*, U.S. Geological Survey (USGS) (1977). First, a tag line (survey tape) was extended across the water surface to mark the cross section. The flow depth was measured using a wading rod placed at even increments along the tag line. The increments ranged from 0.3 to 0.6 m depending on the width of the water surface. At each location, the velocity was measured using a Marsh-McBirney velocity meter. Velocity measurements were conducted using the six-tenths method when the flow depth was less than 0.3 m or two-point method when the flow depth equaled or exceeded 0.3 m. In the six-tenths method, the velocity is recorded at a point located six-tenths of the total depth below the water surface. In the two-point method, the velocity is recorded at two-tenths and eight-tenths of the total depth below the water surface. The average of the two-point measurements is used to compute discharge. The average water temperature was 13 °C in November and 25 °C in June.

Calculation of Discharge and Manning's *n*

The discharge was calculated using the velocity-area method and the midsection method for computing cross-sectional area (USGS 1977). In the midsection

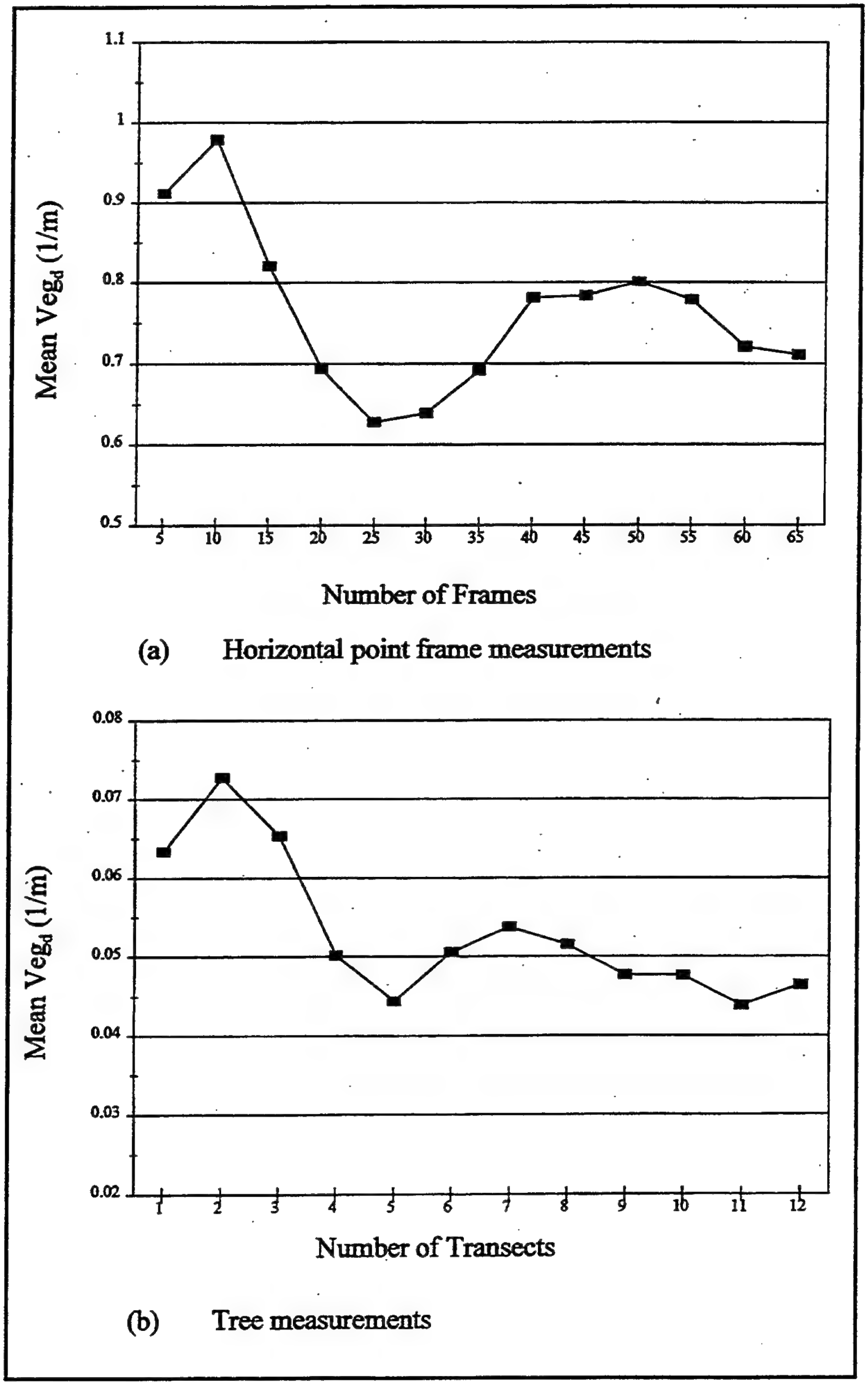


Figure 8. Plots of mean running area

method, the measured velocity and flow depth are assumed to represent the mean values for a rectangular area extending laterally one-half the distance to the adjacent measurement stations. The total discharge is the summation of the products of the partial areas (a_i) and velocities (v_i) for each cross section.

Manning's n was calculated based on the slope of the energy grade line between two adjacent cross sections

$$S_e = \frac{\Delta wse + \Delta h_v}{L} \tag{7}$$

where

Δwse = difference in water surface elevations
Δh_v = difference in velocity head
L = length of reach

The velocity head at each section was calculated as

$$h_v = \frac{\alpha V^2}{2g} \tag{8}$$

where α is the energy coefficient. The value of α was computed as

$$\alpha = \frac{(\Sigma v_i^3 a_i)(\Sigma v_i)^2}{(\Sigma v_i a_i)^3} \tag{9}$$

From Equation 7 and Manning's equation (Equation 1), Manning's n for a channel reach containing two or more cross sections is expressed as

$$n = \frac{1}{Q}\left(\frac{(wse_j - wse_1) + (h_{v_j} - h_{v_1})}{\frac{L_{1.2}}{Z_1 Z_2} + \frac{L_{2.3}}{Z_2 Z_3} + \frac{L_{(j-1).j}}{Z_{(j-1)} Z_j}}\right) \tag{10}$$

where Z_i is a section factor

$$Z_j = A_j R_j^{2/3} \tag{11}$$

and j is the number of cross sections (which are designated as 1, 2, 3, ... (j-1), j with the jth cross section being the farthest upstream). Equation 10 is used to calculate Manning's n for a specified channel reach (e.g., between cross sections or for multiple reaches between cross sections). Manning's n was calculated for the entire channel and five reaches shown on Figure 3. Tables 5 and 6

Table 5
Average Hydraulic Properties, Stillwater, OK, Test Channel, November 1995

Flow No.	Q m^3/s	Reach No.	L m	Y m	A m^2	R m	V m/s	α	S_e	n
1	0.10	1	6	0.16	0.36	0.08	0.28	2.55	0.039	0.128
		2	7	0.20	0.36	0.09	0.27	3.22	0.031	0.123
		3	19	0.21	0.35	0.11	0.28	4.43	0.040	0.148
		4	52	0.21	0.42	0.10	0.27	3.86	0.055	0.201
		5	10	0.24	0.49	0.12	0.23	2.70	0.035	0.209
2	0.33	1	6	0.25	0.86	0.15	0.41	3.73	0.038	0.145
		2	7	0.32	0.91	0.16	0.36	3.33	0.024	0.126
		3	19	0.35	0.93	0.18	0.33	3.41	0.041	0.181
		4	52	0.30	1.03	0.17	0.33	3.07	0.056	0.225
		5	10	0.35	1.20	0.17	0.27	4.99	0.029	0.193
3	0.64	1	6	0.32	1.26	0.19	0.54	2.93	0.047	0.138
		2	7	0.40	1.52	0.21	0.48	3.40	0.016	0.102
		3	19	0.47	1.58	0.23	0.45	3.07	0.041	0.183
		4	52	0.40	1.24	0.19	0.53	2.87	0.057	0.153
		5	10	0.40	1.13	0.18	0.53	3.15	0.032	0.099
4	0.85	1	6	0.37	1.46	0.20	0.57	3.15	0.049	0.130
		2	7	0.43	1.77	0.24	0.51	2.85	0.021	0.114
		3	19	0.49	1.77	0.26	0.49	3.03	0.039	0.162
		4	52	0.43	1.45	0.21	0.55	3.02	0.057	0.145
		5	10	0.44	1.77	0.21	0.50	3.58	0.030	0.127
5	1.34	1	6	0.43	1.90	0.24	0.72	2.57	0.040	0.107
		2	7	0.52	2.34	0.27	0.61	2.50	0.022	0.105
		3	19	0.55	2.28	0.26	0.62	2.49	0.042	0.137
		4	52	0.49	1.92	0.23	0.72	2.79	0.056	0.125
		5	10	0.53	2.39	0.26	0.57	4.02	0.033	0.129
6	1.78	1	6	0.49	2.26	0.26	0.80	1.86	0.047	0.111
		2	7	0.52	2.70	0.28	0.67	2.27	0.030	0.109
		3	19	0.53	2.65	0.26	0.70	2.10	0.041	0.119
		4	52	0.52	2.36	0.24	0.78	2.42	0.054	0.119
		5	10	0.55	2.54	0.26	0.70	2.74	0.042	0.119
7	2.28	1	6	0.50	2.68	0.28	0.87	1.68	0.050	0.112
		2	7	0.55	2.87	0.29	0.81	1.86	0.022	0.081
		3	19	0.56	2.82	0.28	0.81	2.02	0.043	0.109
		4	52	0.56	2.87	0.30	0.82	2.67	0.053	0.127
		5	10	0.64	3.10	0.32	0.75	2.90	0.040	0.127
8	3.07	1	6	0.56	3.10	0.30	1.01	1.88	0.034	0.084
		2	7	0.61	3.33	0.32	0.94	1.76	0.039	0.098
		3	19	0.62	3.22	0.30	0.97	1.75	0.037	0.089
		4	52	0.62	3.15	0.30	0.98	2.29	0.055	0.106
		5	10	0.66	3.48	0.32	0.88	2.73	0.036	0.101
9	3.97	1	6	0.61	3.63	0.33	1.09	1.73	0.060	0.107
		2	7	0.64	4.00	0.34	1.00	1.55	0.023	0.074
		3	19	0.67	3.80	0.33	1.10	1.54	0.040	0.090
		4	52	0.64	3.73	0.33	1.11	2.30	0.055	0.102
		5	10	0.69	4.15	0.34	0.96	2.79	0.036	0.096

Table 6
Average Hydraulic Properties, Stillwater, OK, Test Channel, June 1996

Flow No.	*Q* m^3/s	Reach No.	*L* m	*Y* m	*A* m^2	*R* m	*V* m/s	α	S_e	*n*
1	0.11	1	6	0.18	0.41	0.09	0.26	2.88	0.045	0.150
		2	7	0.18	0.32	0.08	0.35	2.70	0.034	0.099
		3	19	0.23	0.29	0.09	0.42	2.95	0.035	0.096
		4	52	0.23	0.30	0.09	0.39	3.15	0.057	0.125
		5	10	0.20	0.29	0.09	0.38	2.65	0.042	0.108
2	0.34	1	6	0.26	0.74	0.13	0.42	2.23	0.035	0.105
		2	7	0.27	0.73	0.13	0.42	2.38	0.045	0.117
		3	19	0.32	0.71	0.14	0.50	2.51	0.035	0.106
		4	52	0.30	0.62	0.14	0.58	2.14	0.056	0.117
		5	10	0.27	0.55	0.13	0.66	2.07	0.034	0.175
3	0.66	1	6	0.34	1.16	0.18	0.58	1.82	0.054	0.130
		2	7	0.34	1.18	0.19	0.55	2.12	0.029	0.100
		3	19	0.35	1.12	0.19	0.66	2.23	0.039	0.108
		4	52	0.35	0.89	0.17	0.82	1.81	0.055	0.098
		5	10	0.37	0.87	0.16	0.72	2.06	0.044	0.081
4	0.93	1	6	0.38	1.41	0.20	0.62	2.11	0.052	0.118
		2	7	0.41	1.51	0.22	0.59	1.72	0.026	0.094
		3	19	0.41	1.42	0.21	0.72	1.92	0.041	0.105
		4	52	0.38	1.11	0.18	0.90	2.05	0.055	0.087
		5	10	0.41	1.13	0.18	0.86	2.31	0.039	0.076
5	1.39	1	6	0.44	1.79	0.23	0.80	1.72	0.051	0.109
		2	7	0.43	1.85	0.25	0.76	1.48	0.039	0.104
		3	19	0.43	1.75	0.24	0.90	1.63	0.036	0.088
		4	52	0.40	1.31	0.19	1.05	1.72	0.057	0.075
		5	10	0.41	1.39	0.20	0.94	1.93	0.034	0.062
6	1.86	1	6	0.47	2.11	0.25	0.87	1.93	0.051	0.101
		2	7	0.46	2.08	0.27	0.89	1.42	0.039	0.092
		3	19	0.46	1.95	0.25	0.94	1.68	0.036	0.077
		4	52	0.43	1.61	0.22	1.18	1.75	0.056	0.075
		5	10	0.44	1.77	0.23	1.14	1.82	0.037	0.069
7	2.28	1	6	0.49	2.48	0.27	0.94	1.86	0.056	0.107
		2	7	0.47	2.41	0.28	0.95	1.41	0.036	0.085
		3	19	0.47	2.26	0.26	1.04	1.42	0.038	0.077
		4	52	0.44	1.92	0.22	1.25	1.59	0.055	0.072
		5	10	0.52	2.07	0.23	1.12	1.78	0.032	0.061
8	2.97	1	6	0.53	3.11	0.30	1.02	1.79	0.049	0.102
		2	7	0.56	3.02	0.30	1.00	1.55	0.029	0.077
		3	19	0.62	2.87	0.28	1.04	1.56	0.035	0.075
		4	52	0.56	2.49	0.25	1.18	1.80	0.057	0.080
		5	10	0.56	2.66	0.28	1.10	1.92	0.033	0.070
9	3.42	1	6	0.59	3.47	0.32	0.99	1.80	0.052	0.108
		2	7	0.58	3.43	0.32	0.98	1.58	0.038	0.092
		3	19	0.58	3.17	0.30	1.10	1.58	0.037	0.078
		4	52	0.56	2.83	0.27	1.21	1.95	0.055	0.081
		5	10	0.56	3.04	0.30	1.13	2.02	0.046	0.085

summarize the values of Manning's n and other average hydraulic properties for the five reaches. The Manning's n values for the entire channel based on the six cross sections are listed in Table 7.

Table 7
Discharge and Manning's *n* Values for Stillwater, OK, Test Channel

Flow No.	November[1]		June[2]		Difference, %
	Q m^3/s	n	Q m^3/s	n	
1	0.10	0.176	0.11	0.117	51
2	0.33	0.199	0.34	0.109	83
3	0.64	0.147	0.66	0.099	48
4	0.85	0.143	0.93	0.090	59
5	1.3	0.125	1.4	0.078	60
6	1.8	0.118	1.9	0.077	53
7	2.3	0.119	2.3	0.074	61
8	3.1	0.100	3.0	0.079	27
9	4.0	0.098	3.4	0.083	18

[1] Debris present and leaves absent.
[2] Debris absent and leaves present.

Discussion of Results

Evaluation of Manning's *n*

Table 8 presents the percentage difference in Manning's n values for the five reaches and the nine flow tests conducted in both November and June. The values are expressed as a percentage of the June value. The two primary differences in the channel conditions between the two periods are that, in November, the trees and shrubs were devoid of leaves, and vegetative debris, such as dry leaves and wood, were present. The values in Table 8 reflect both the influence of the debris, which would increase the value of Manning's n, and the lack of leaves, which would decrease Manning's n relative to the June value.

It is apparent from Tables 7 and 8 that the presence of debris had significant influence on the flow resistance and measured value of Manning's n. Table 7 indicates an increase in the average percent difference in Manning's n from upstream to downstream (reach 1 to 5). The average percent difference tends to decrease with increasing discharge particularly for flow numbers 7 through 9. Debris was accumulated on the channel banks and lodged in the vegetation. Debris was abundant in reaches 4 and 5, which is evident by the large percentage differences for these reaches. The Manning's n values for reaches 4 and 5 in

Table 8
Percentage Difference Between Manning's *n* Values for November 1995 and June 1996 for Nine Flows and Five Channel Reaches

	Reach				
Flow No.	1	2	3	4	5
1	-15	25	55	60	94
2	38	8	71	93	158
3	6	2	69	57	22
4	11	21	54	66	68
5	-1	1	55	68	109
6	9	19	54	60	71
7	5	-6	40	76	107
8	-18	28	18	32	44
9	-1	-20	15	26	13
Average	4	9	48	60	76

November were 60 and 76 percent greater, respectively, than June due to the presence of debris.

Evaluation of drag coefficient

Fischenich (1996) presented Equation 2 for estimating Manning's n for channels in which the vegetation is not submersed.

$$n = k_n R^{2/3} \left[\frac{C_d Veg_d}{2g} \right]^{1/2}$$

Equation 2 is limited because there is little information available concerning the drag characteristics of vegetation. Through dimensional analysis, it can be demonstrated that the coefficient of drag C_d is a function of the Reynolds number Re (Vogel 1981)

$$C_d = (Re)^a = \left(\frac{Vl}{\nu} \right)^a \tag{12}$$

where
- a = coefficient
- l = characteristic length
- ν = kinematic viscosity

The characteristic length l is expressed as the hydraulic radius R in open channel flow. However, for submersed objects Re is typically based on the greatest length of the object in the direction of flow (Vogel 1981). The characteristic length that should be used to define the Re is unclear for an open channel with submersed objects such as vegetation. Because the local flow velocity through vegetation can vary substantially, the velocity that should be used to define Re is equally ill defined. In this study, the hydraulic radius R and the mean velocity V were used to define Re.

The value of C_d for the vegetation in the test channel was calculated by solving Equation 2 for C_d using the values of Veg_d, Manning's n, and hydraulic radius R for November and June flow tests. The drag coefficient C_d was calculated for the nine test discharge rates for a total of 18 values. The calculated C_d was plotted against both the product of the average velocity times average hydraulic radius VR (Figures 9 and 10) and the Re (Figures 11 and 12) for the channel conditions in November 1995 (debris present and green foliage absent) and June 1996 (debris absent and green foliage present), respectively. The plots indicate that the C_d approaches a constant value at high velocities.

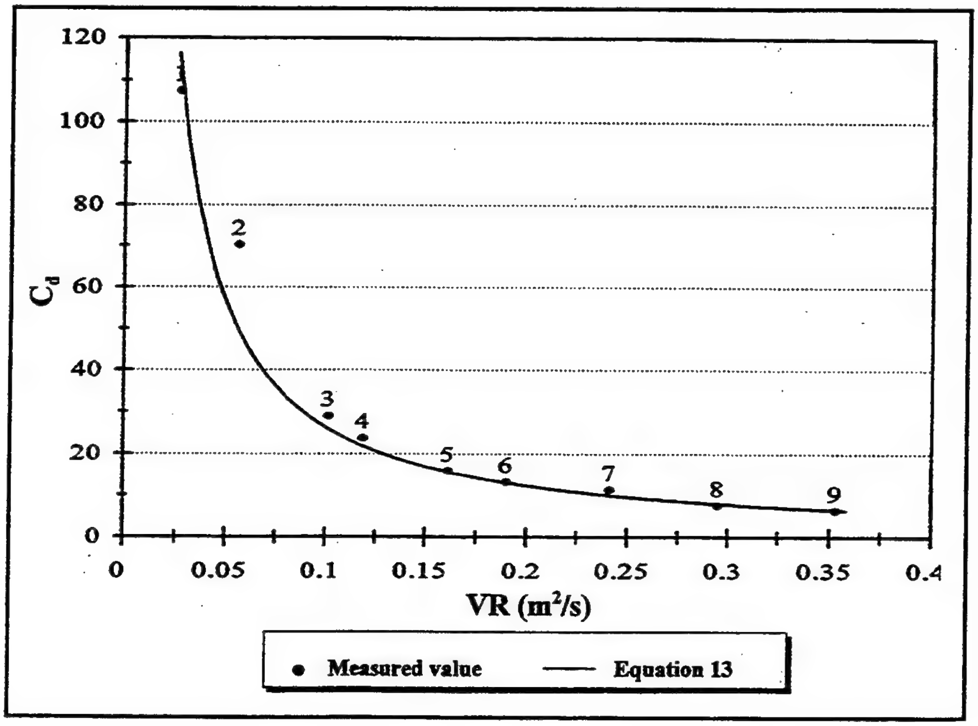


Figure 9. C_d as a function of VR for nine test discharges based on measurements conducted in November 1995 with debris present and leaves absent

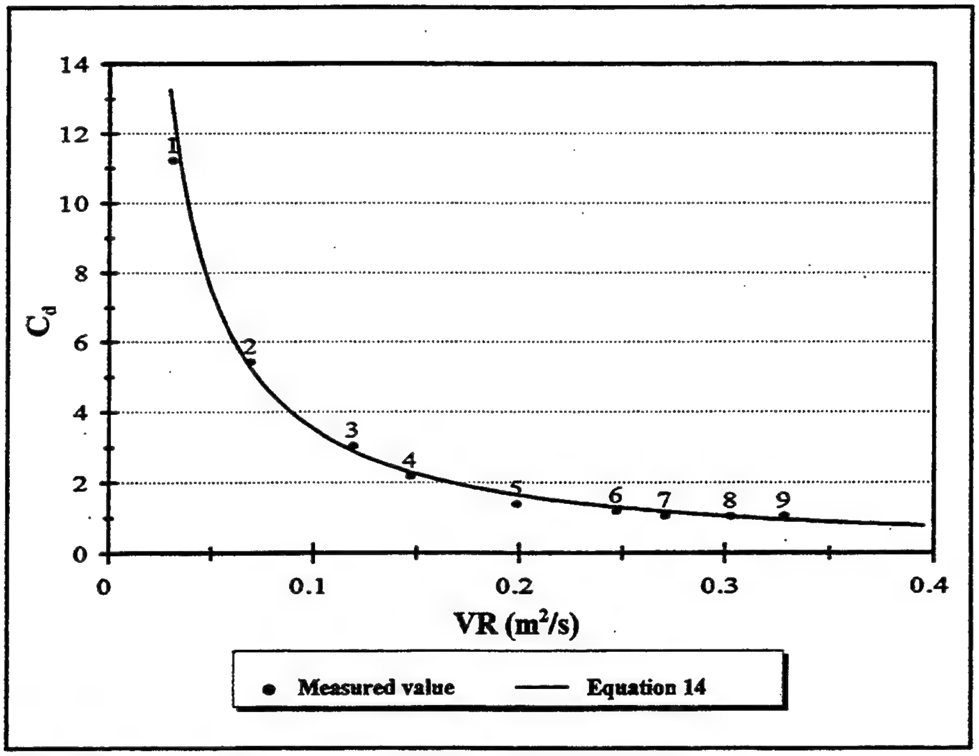


Figure 10. C_d as a function of *VR* for nine test discharges based on measurements conducted in June 1996 with debris absent and leaves present

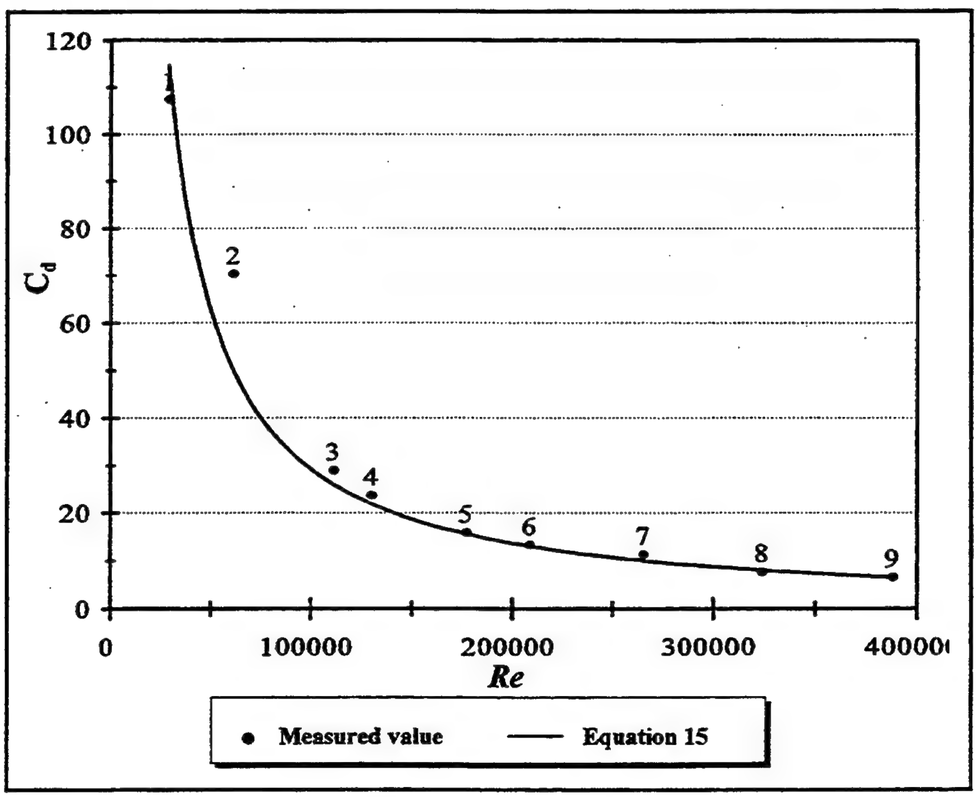


Figure 11. C_d as a function of *Re* for nine test discharges based on measurements conducted in November 1995 with debris present and leaves absent

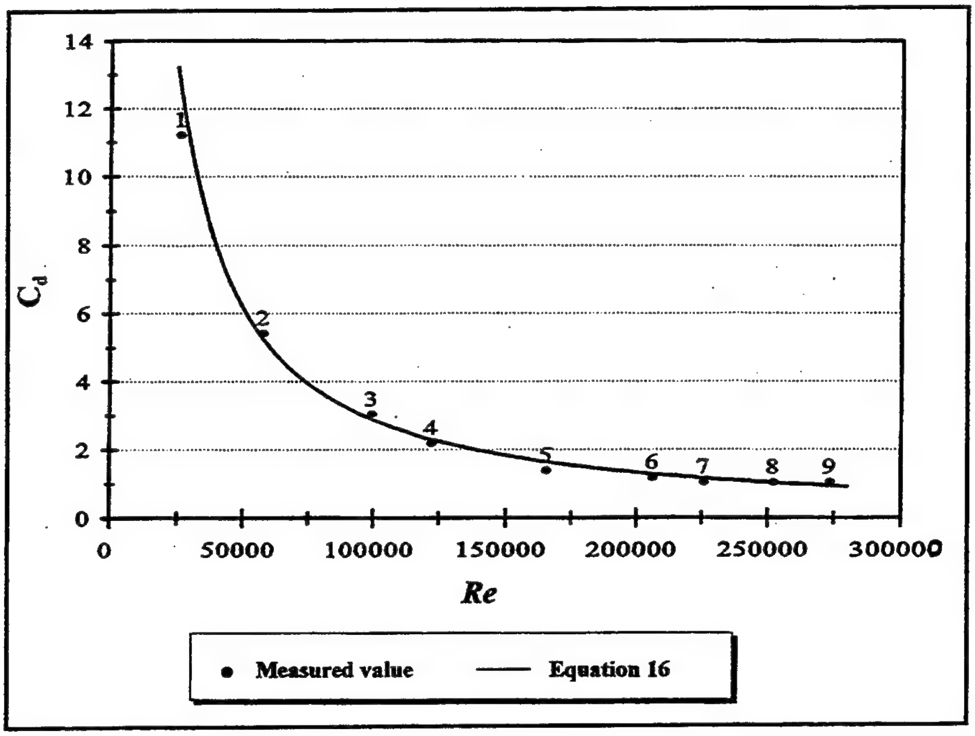


Figure 12. C_d as a function of *Re* for nine test discharges based on measurements conducted in June 1996 without debris and with leaves

Curve fits for the data were obtained by regression using the method of least squares. The relation between C_d and VR under conditions with debris present and leaves absent from the trees and shrubs was

$$C_d = 2.1(VR)^{-1.1} \tag{13}$$

and with debris removed and leaves present was

$$C_d = 0.28(VR)^{-1.1} \tag{14}$$

The coefficients of determination R^2 for the regression functions were 0.99 and 0.98 for Equations 13 and 14, respectively. A graph of Equations 13 and 14 on log-log scale (Figure 13) depicts two curves having the same slope; however, the presence of debris in the channel resulted in a drag coefficient C_d that was 7.5 times greater than without debris for a given VR product.

The relation between C_d and Re with debris present and leaves absent was (Figure 11)

$$C_d = 9.3x10^6(Re)^{-1.1} \tag{15}$$

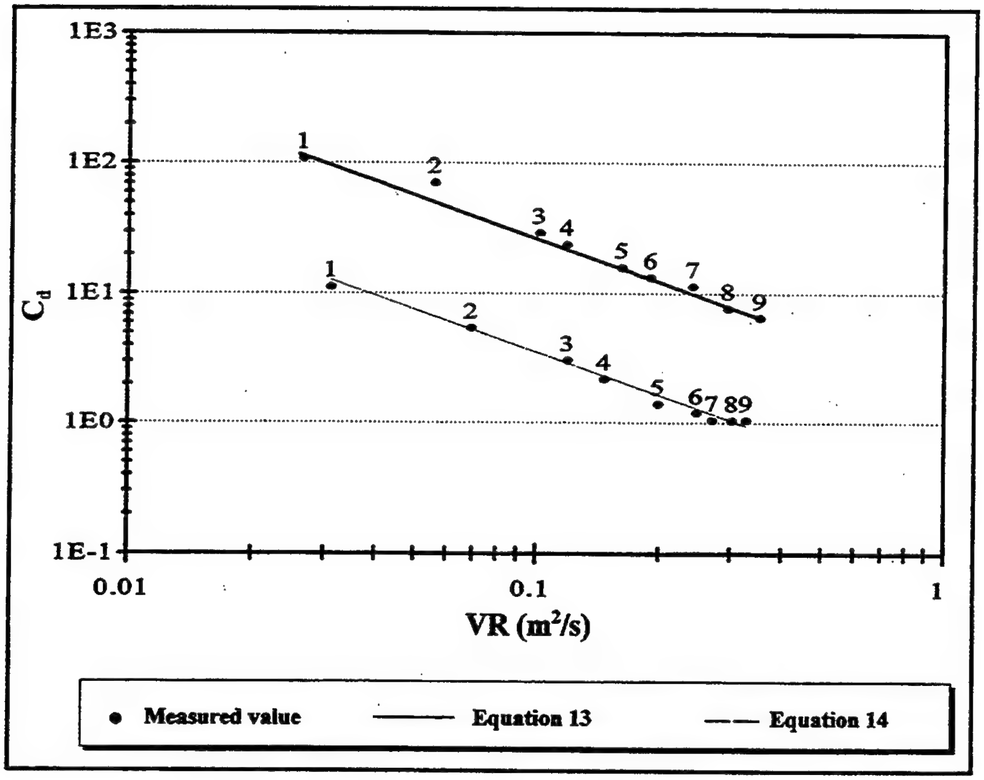


Figure 13. C_d as a function of VR plotted on log-log scale for conditions with debris and without leaves (Equation 13) and without debris and with leaves (Equation 14)

and without debris and leaves present (Figure 12)

$$C_d = 9.1x10^5(Re)^{-1.1} \tag{16}$$

The kinematic viscosity ν of the water was estimated to be 9.1×10^{-7} m²/s based on a water temperature of 13.3 °C in November 1995 and 1.2×10^{-6} m²/s based on water temperature of 24.4 °C in June 1996. A graph of Equations 15 and 16 on log-log scale (Figure 14) depicts two curves having the approximately the same slope. The magnitude of C_d for a specific Re was 10.2 times greater in November 1995 than in June 1996 presumably because of the presence of debris and, to a lesser extent, the exclusion of the grass from the Veg_d term.

Assumptions of the methodology

Equation 2 was derived from the de Saint Venant and Manning equations for open channel flow based on several assumptions:

a. Flow depth is less than the height of the vegetation.

b. Vegetation is randomly distributed within the control volume.

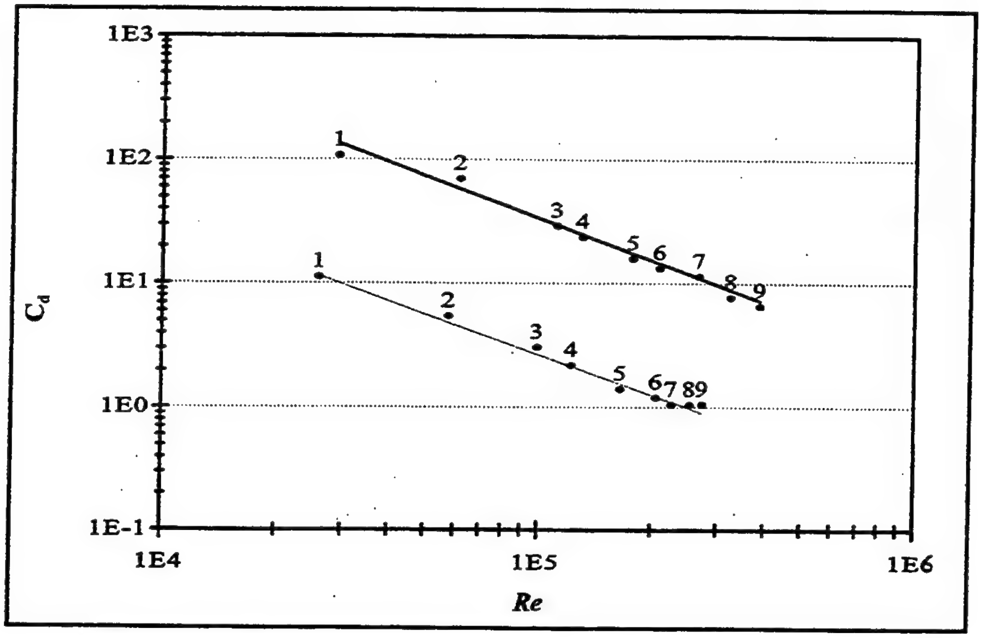


Figure 14. C_d as a function of *Re* plotted on log-log scale for conditions with debris and without leaves (Equation 15) and without debris and with leaves (Equation 16)

c. Resistance due to surface friction, flow obstructions, and changes in channel geometry is negligible compared with vegetative effects.

d. Pressure distribution is hydrostatic.

e. Flow velocity over the channel cross section is uniform.

f. Steady, uniform flow conditions exist.

The assumptions inherent in Equation 2 were employed in order to reduce the number of required input parameters and provide a practical procedure for obtaining reasonable estimates of flow resistance and channel capacity. Many of these simplifying assumptions were violated. Grasses, vines, and shrubs were sometimes submersed near the center of the V-shaped test channel where the flow velocity and depth were greatest. Flippin-Dudley et al. (in preparation) demonstrated that the vegetation in the test channel was probably not randomly distributed and is rarely completely random in nature (Bonham 1989). Surface friction may have accounted for approximately 19 percent on average of the total resistance in November and 29 percent in June, assuming resistance factors are additive and a surface Manning's *n* value of 0.025 (Arcement and Schneider 1989). Extreme variation in transverse flow velocity was observed, as evidenced by the high values of the energy coefficients presented in Tables 5 and 6.

Another assumption of this study was that the coefficient of drag and density of vegetation remained constant throughout the duration of the test. An average vegetation density was used to represent the entire length of the channel under

investigation. Both the vegetation density and the drag coefficient decreases as velocity increases and the vegetative elements are deflected in the direction of flow.

The combined effect of the assumptions of the method must be absorbed by the drag coefficient. Laboratory research has demonstrated that the coefficient of drag for flow around cylinders and similar objects is approximately 1.0 (e.g., Petryk 1969 or Tseng 1974). The drag coefficient C_d associated with the June measurements was approximately 1.0 for $Re > 2 \times 10^6$ (Figure 11), which indicates that the assumptions made with respect to the flow and vegetative conditions were reasonable for the analysis conducted using June data. The coefficient of drag was approximately 6.5 for $Re > 2 \times 10^6$ measured in November. The high coefficient of drag is primarily due to the presence of debris and, to a lesser extent, grass that was not included in the Veg_d parameter used in the development of Equation 13 and Equation 15.

Evaluation of debris

Flow resistance due to the presence of debris can be evaluated by extending Equation 2 to include the effects of debris. Assuming that the drag characteristics of debris are the same as those for the associated vegetation,

$$n = k_n R^{2/3} \left[\frac{C_d (Veg_d + Deb_d)}{2g} \right]^{1/2} \tag{17}$$

where Deb_d is the frontal area of the debris projected onto a plane perpendicular to the direction of flow and the other parameters are as defined previously.

To assess the value of Deb_d, the drag coefficient C_d for $Re > 2 \times 10^6$ was assumed to equal unity, and the density of the grass in November was equal to that measured in June. The Veg_d including the grass was 0.322/m ((68 grass hits + 21 stem hits) divided by 906 points/0.3 m). Equation 17 was solved for Deb_d based on flow measurements conducted in November. The average Deb_d is estimated to be 0.88/m, which would account for approximately 73 percent of the Veg_d and Deb_d combined.

Application of the Methodology

The proposed equations for C_d, Equations 13 through 16, can be applied in conjunction with Equation 2 to determine the Manning's n for channels having vegetative and debris conditions similar to those tested in this study. Arcement and Schneider (1989) presented data for several wooded forest floodplains in Mississippi and Alabama. The data presented for Pea Creek (Ming, Colson, and Arcement 1979), Coldwater River (Colson, Ming, and Arcement 1979a), Thompson Creek (Colson, Arcement, and Ming 1979), and Yockanookany River (Colson, Ming, and Arcement 1979b) were used to demonstrate use of the

equations to predict Manning's n for a vegetated channel. A summary of the relevant parameters is presented in Table 9.

Arcement and Schneider (1989) presented photographs of each stream accompanied by a description of the floodplain and vegetation characteristics including the Veg_d, type of vegetation and influence of ground cover and obstructions. The flow measurements were conducted in winter when no leaves were present on the trees, and Veg_d was determined from direct measurement of tree and large vine diameters. Ground cover and undergrowth, such as shrubs and grass, and vegetative debris were not included in the Veg_d term.

The graph of the predicted versus measured Manning's n values using Equations 13 and 14 to predict the drag coefficient C_d is shown in Figure 15. The n values predicted using Equation 13 plot close to the line of perfect agreement while Equation 14 substantially underestimated the n value. This result is not surprising because the contribution of vegetative debris and undergrowth were not included in the Veg_d measurements conducted by Arcement and Schneider (1989).

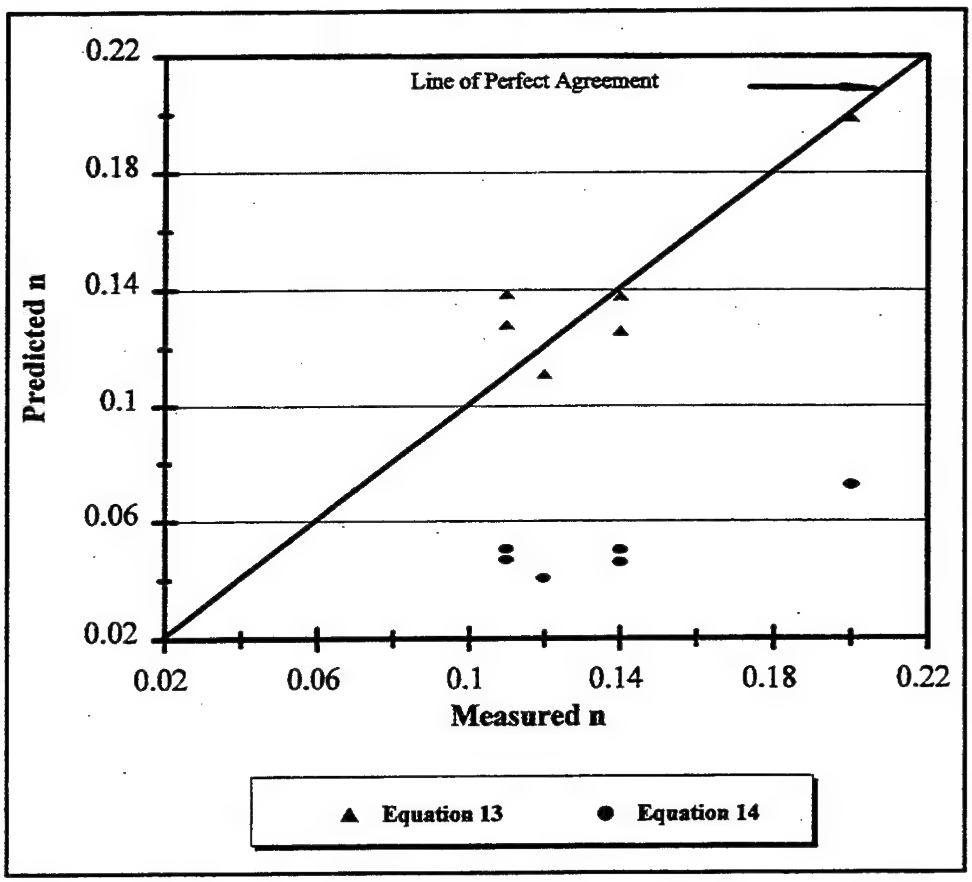


Figure 15. Predicted versus measured Manning's n for stream data presented by Arcement and Schneider (1989)

Table 9
Veg_d and Hydraulic Parameters for Stream Data Presented in Arcement and Schneider (1989)

	Section	Veg_d 1/m	Q m³/s	V m/s	R m	VR m²/s	Measured n	Equation 13		Equation 14	
								C_d	Predicted n	C_d	Predicted n
Pea Creek	5	0.028	50.4	0.182	0.897	0.163	0.14	15.4	0.14	2.1	0.05
Pea Creek	4	0.033	50.4	0.239	0.683	0.163	0.14	15.4	0.13	2.1	0.05
Coldwater River	2	0.025	125	0.180	0.696	0.125	0.11	20.6	0.13	2.7	0.05
Coldwater River	2	0.030	125	0.180	0.696	0.125	0.11	20.6	0.14	2.7	0.05
Thompson Creek	9	0.038	108	0.117	0.695	0.081	0.20	33.2	0.20	4.4	0.07
Yockanoonkany River	5	0.027	289	0.265	0.961	0.254	0.12	9.5	0.11	1.3	0.04

3 Conclusions and Recommendations for Future Research

Prediction of Flow Resistance in Vegetated Open Channel and Floodplains

A vegetated channel located at the ARS Outdoor Hydraulic Laboratory near Stillwater, OK, was used to demonstrate the application of the horizontal point frame and its role in a comprehensive approach to predicting resistance to flow. The vegetation measurements were used in conjunction with flow measurements in the test channel to develop a relationship for the drag coefficient of the vegetation C_d. Flow tests were conducted for two vegetative conditions: (a) in November 1995 when leaves on the trees and shrubs were absent and debris was present, and (b) in June 1996 when leaves were present and the debris was removed. An evaluation of the data indicated the following:

- The value of C_d can be related to the product of the velocity and hydraulic radius *VR* and/or the Reynolds number *Re*.
- With leaves absent and debris present, $C_d = 2.1(VR)^{-1.1}$, Equation 13.
- With leaves present and debris absent, $C_d = 0.28(VR)^{-1.1}$, Equation 14.
- With leaves absent and debris present, $C_d = 9.3 \times 10^6(Re)^{-1.1}$, Equation 15, based on a kinematic viscosity of 9.1×10^{-7} m^2/s.
- With leaves and debris absent, $C_d = 9.1 \times 10^5(Re)^{-1.1}$, Equation 16, based on a kinematic viscosity of 1.2×10^{-6} m^2/s.
- C_d was approximately unity for June measurements at $Re > 2 \times 10^6$, which is consistent with laboratory model tests performed by others.

- C_d was approximately 6.5 for November measurements at $Re > 2 \times 10^6$, greater than the expected value of unity primarily due to the presence of debris.

- Equations 13 or 15 can be used in conjunction with Fischenich's (1996) equation (Equation 2) to determine Manning's *n* when debris is not present and vegetation is not submersed.

- Equations 14 or 16 can be used in conjunction with Fischenich's (1996) equation to determine Manning's *n* when debris is present, leaves on trees and shrubs are absent, and minimal ground cover is present.

- Using Equations 14 or 16, the predicted Manning's *n* was within an average of 10 percent of the measured value for four streams in Mississippi and Alabama.

Recommendations for Future Research

Vegetation plays a vital role in the environmental balance of riparian ecosystems. Standard methods for characterizing vegetation and predicting flow resistance allow interdisciplinary teams to address practical problems using comparable data sets and analysis. Engineers could collaborate with other scientists to determine the most beneficial plan to mitigate flood hazards and restore or maintain the equilibrium of a stream system. Once a common foundation and interpretation of the design parameters can be reached, the findings by engineering and scientific disciplines can be better incorporated into river management practices. Pursuant to this end, future research should focus on the following:

- The use of Veg_d as a parameter for classification and optimization of the flow resistance, erosion and sedimentation, bank stability, habitat and aesthetic properties of riparian vegetation.

- The optimum quadrat size and shape for the direct measurement of tree trunks used to determine Veg_d.

- The relation between the Veg_d measured without flow and the actual Veg_d with flow for flexible vegetation.

- Quantitative methods for the measurement of vegetative debris.

- A vegetative parameter that characterizes the spatial patterns and distribution of vegetation (i.e., clustering, etc.).

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13. ABSTRACT *(Maximum 200 words)*

Riparian vegetation is an integral component of the flood channel because it stabilizes streambanks, provides shade that prevents excessive water temperature fluctuations, supports wildlife, and performs an essential role in nutrient cycling and water quality. Concurrent with the benefits provided by riparian vegetation are the issues pertaining to flood hazard mitigation. Vegetation increases flow resistance, which has a direct effect on the discharge capacity and the level of flood protection provided by the channel.

Several methods have been proposed for determining Manning's *n* in vegetated channels. These methods recognize that the physical characteristics of the vegetation are important factors in evaluating flow resistance. However, minimal research has been conducted to quantify the density and drag characteristics of vegetation. A cooperative study between the U.S. Army Corps of Engineers and Colorado State University was conducted to develop a method of computing flow resistance in vegetated channels and floodplains.

A field study was performed in a vegetated channel located near Stillwater, OK, as a part of the development of a comprehensive approach to predicting resistance to flow using the Fischenich equation. The channel was characterized for geometry, slope, and vegetation density. A series of nine flows was conveyed through the channel, and

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velocity and depth measurements were obtained for two vegetative conditions: (a) without leaves on trees and shrubs and with vegetative debris present, and (b) with leaves on trees and shrubs and without vegetative debris.

The vegetation and flow measurements were used to develop a relation between the coefficient of drag and Reynolds number *Re* for the two conditions investigated. For $Re > 2 \times 10^6$, the drag coefficient associated with the latter condition was approximately equal to unity, which is consistent with laboratory model test results reported by others. The drag coefficient for a specified *Re* was 10.2 times greater for the former condition primarily due to the presence of debris. The relations for drag can be input into the Fischenich equation to solve for Manning's *n* for channels with similar vegetative conditions. Manning's *n* was predicted within an average of 10 percent for four streams located in Mississippi and Alabama using the approach.